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Exploratory Analysis on Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G

Adarsh Aithal
Final Year M.S. (ortho) Scholar, KMCRI, Hubballi, India
ORCID-ID: 0009-0005-4483-9355; E-mail: aithaladarsh@gmail.com

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ABSTRACT

Purpose: *The purpose of this research analysis is to evaluate the technical feasibility and systemic impact of integrating AR/VR and 6G technology into remote spine surgery. The study specifically investigates how these advancements can enhance surgical precision while democratizing access to elite medical expertise in underserved regions. Additionally, it utilizes strategic frameworks like SWOC and ABCD to identify infrastructural barriers and assess the value propositions for all healthcare stakeholders.*
Design/Methodology: *This exploratory case study is based on data gathered from reliable sources such as websites, Google Scholar, and AI-driven GPT tools, and is examined using suitable analytical frameworks aligned with the study's objectives.*
Result/Analysis: *The analysis reveals that integrating AR/VR with 5G/6G-enabled telesurgery significantly enhances surgical precision, visualization, and real-time decision-making in complex spine procedures. It demonstrates strong potential in reducing complications, radiation exposure, and bridging the global expertise gap through remote intervention capabilities. However, the findings also highlight critical challenges such as latency sensitivity, high infrastructure costs, and medico-legal complexities that must be addressed for large-scale adoption.*
Research Limitations/Implications: *The study is limited by its reliance on qualitative, review-based analysis without empirical clinical validation, which may restrict the generalizability of findings across real-world surgical settings. The implications suggest a strong need for future experimental research, standardized regulatory frameworks, and robust infrastructure development to enable safe and scalable adoption of 6G-enabled remote spine surgery.*
Originality/Value: *The study offers originality by integrating AR/VR, robotic spine surgery, and emerging 5G/6G connectivity into a unified "Smart Surgery" framework, supported by strategic models like SWOC and ABCD for comprehensive evaluation. Its value lies in proposing a futuristic, borderless healthcare model that not only enhances surgical precision but also addresses global disparities in access to specialized spine care.*
Type of paper: *Qualitative Exploratory Review-Based Analysis*.

Keywords: Smart Spine Surgery, AR/VR Technology, Remote Telesurgery, 5G/6G Enabled Smart Surgery, Remote Telesurgery, 6G Connectivity, Augmented Reality, Spine Deformity, SWOC Analysis, ABCD Framework, Impact Analysis

1. INTRODUCTION :

1.1 Background:

The historical trajectory of spinal surgery has been defined by a relentless pursuit of visualization and precision, evolving from invasive "Open" procedures to the current "Smart" paradigm. Traditionally, spinal interventions were characterized by large incisions and extensive muscle stripping to provide surgeons with direct line-of-sight to the vertebral column (Kuhn et al. (2024). [1]). While effective, these "open" techniques were associated with significant blood loss, prolonged hospital stays, and extensive postoperative recovery periods due to the collateral damage inflicted on paraspinal musculature (Nadeem-Tariq et al. (2025). [2]). This era relied heavily on the surgeon's tactile feedback and 2D radiographic snapshots, which offered limited guidance during the high-stakes navigation of neurovascular structures.

The transition toward Minimally Invasive Spine Surgery (MISS) in the late 20th and early 21st centuries marked the first major shift toward modernizing spinal care. This phase introduced tubular retractors and endoscopic portals, allowing surgeons to perform complex decompressions and fusions through "keyhole" incisions (Chandan Reddy et al. (2025). [3]). However, the reduction in physical exposure created a "visualization gap," where surgeons could no longer see the anatomy directly. To compensate, the industry integrated intraoperative fluoroscopy and basic computer-assisted navigation systems. While these tools improved accuracy, they also increased radiation exposure for the surgical team and introduced a "cognitive shift" as surgeons had to frequently look away from the patient to view external monitors (Burström et al. (2021). [4]).

The current "Smart" surgery era represents the convergence of Extended Reality (XR) and robotics, effectively bridging the visualization gap while enhancing human dexterity. "Smart" spine surgery is defined by the use of Augmented Reality (AR) headsets that project holographic 3D anatomical models directly onto the surgical field, providing surgeons with "X-ray vision" (Cofano et al. (2021). [5]). Unlike earlier navigation, these smart systems utilize real-time 3D anatomical registration, ensuring that the digital overlay moves in perfect synchronization with the patient's breathing and positioning (Nadeem-Tariq et al. (2025). [2]), This evolution has moved the field from a "hardware-centric" approach to a "data-centric" one, where precision is determined by algorithmic accuracy and real-time feedback loops.

The most futuristic layer of this evolution involves the integration of high-speed connectivity to enable Remote Telesurgery. By leveraging 5G and emerging 6G networks, the "Smart" ecosystem now allows for the physical decoupling of the surgeon from the operating theater. Telesurgery utilizes a master-slave architecture where a remote expert can manipulate a patient-side robot with sub-millimeter precision across vast distances (Ding et al. (2025). [6]). This milestone is critical for global healthcare, as it allows for the democratization of elite surgical expertise, ensuring that patients in underserved regions receive the same caliber of care as those in urban medical hubs (Jha et al. (2026). [7]).

Finally, the shift to 6G-enabled "Smart" surgery addresses the final frontier of telesurgery: haptic and visual synchronization. While 5G enabled basic remote operation, 6G targets sub-millisecond latency, which is essential for transmitting the "tactile feel" of bone and ligament resistance back to the remote surgeon (Ding et al. (2025). [6]). This "Internet of Skills" ensures that the surgeon's sensory experience is indistinguishable from being physically present at the bedside. As the field moves toward 2030, the "Smart" spine surgery paradigm is set to become an autonomous, borderless digital ecosystem, fundamentally redefining the relationship between technology, geography, and human healing (Misra et al. (2025). [8]).

1.2 Problem Statement:

The primary challenge in spinal surgery arises from the unforgiving anatomical landscape of the vertebral column, where the margin for error is often less than a single millimeter. Spinal interventions carry exceptionally high stakes due to the dense proximity of critical neurovascular structures, including the spinal cord, nerve roots, and the vertebral arteries (Ding et al. (2025). [6]). In complex procedures such as pedicle screw fixation or deformity correction, a minor trajectory deviation can lead to catastrophic permanent neurological deficits, vascular injury, or dural tears (Burström et al. (2021). [4]). Despite these risks, traditional techniques have long relied on "free-hand" placement or 2D fluoroscopic guidance, both of which suffer from significant variability in accuracy and subject the surgical team to cumulative ionizing radiation (Chandan Reddy et al. (2025). [3]).

Furthermore, current "local-only" navigation systems present significant operational limitations that hinder the widespread adoption of precision orthopaedics. Existing optical and electromagnetic navigation platforms require a bulky physical footprint within the operating theater, often interfering with the surgical workflow and line-of-sight (Nadeem-Tariq et al., (2025). [2]). These systems are "local" in the sense that they tether the surgeon to a specific workstation and a line-of-sight monitor, forcing a "cognitive attention shift" where the surgeon must look away from the patient to a screen to confirm trajectories (Cofano et al. (2021). [5]). This disconnection between the surgeon's visual focus and the physical operative field increases the mental workload and introduces a risk of "inattentional blindness" during critical maneuvers (Kuhn et al., (2024). [1]).

The lack of high-fidelity remote capabilities also creates a significant "expertise gap" in global spinal care. Traditional navigation systems are localized assets that cannot bridge the geographical divide between elite specialists and underserved patients in rural or remote areas (Jha et al. (2026). [7]). Without the integration of ultra-low-latency 6G connectivity and immersive AR/VR, complex spinal expertise remains concentrated in urban "Centres of Excellence," leaving a vast majority of the global population with limited access to life-changing surgical precision (Misra et al. (2025). [8]). Therefore, the central problem lies in the inability of current local-only infrastructures to provide a seamless, borderless, and heads-up surgical environment that matches the high stakes of spinal anatomy (Tian et al., 2020).

1.3 Rational for 5G/6G:

The evolution of wireless connectivity from the fifth generation (5G) to the emerging sixth generation (6G) is the fundamental enabler for the transition of "Smart" spine surgery from local navigation to global remote intervention. Current 5G technology serves as a critical "bridge" because it introduced the first reliable framework for Ultra-Reliable Low-Latency Communication (URLLC), which is essential for medical telerobotics (Tian et al. (2020). [9]). With peak data rates of 10–20 Gbps and an end-to-end latency reduced to the 20–50 millisecond range, 5G has proven effective for "supervised" telesurgery, where a remote expert provides guidance or performs slow, deliberate tasks like pedicle screw placement (Jha et al. (2026). [7]). However, 5G networks still face significant "jitter" and signal degradation over transcontinental distances, which can lead to desynchronized haptic and visual feeds that are unacceptable in high-stakes spinal deformity corrections (Misra et al. (2025). [8]).

While 5G provides the connectivity, 6G is the "destination" for truly immersive and autonomous spinal care due to its target of sub-millisecond latency (<1ms). The rationale for 6G lies in its ability to support the "Internet of Skills," where the bandwidth (up to 1 Tbps) is sufficient to transmit high-definition 3D holographic video and multi-dimensional haptic data simultaneously (Ding et al. (2025). [6]). In spine surgery, where the tactile "feel" of bone density is as important as the visual field, 6G ensures that haptic feedback loops are near-instantaneous, eliminating the "perceptual gap" that currently plagues remote surgery (Ding et al. (2025). [6]). This level of reliability—approaching 99.99999%—is required to ensure that a remote surgeon can respond to a sudden neurovascular complication with the same speed as if they were physically present at the patient's side (Jha et al. (2026). [7]).

Furthermore, the transition to 6G enables the integration of "Smart" edge computing and Artificial Intelligence (AI) directly within the network fabric. 6G is designed to facilitate the real-time processing of "Digital Twins," allowing for complex biomechanical simulations of the spine to occur within the network before the command reaches the robot (Chandan Reddy et al. (2025). [3]). This predictive capability is essential for overcoming the physical laws of light-speed travel over vast distances, essentially "masking" any residual latency with AI-driven motion prediction (Misra et al. (2026). [8]). Consequently, 6G is not merely a faster version of its predecessor; it is a specialized medical infrastructure that transforms spine surgery into a borderless, latency-free digital service (Li, et al. (2026). [10]).

1.4 Scope of the Paper:

The scope of this exploratory analysis is specifically bounded by the intersection of advanced immersive visualization, robotic orthopaedics, and ultra-high-speed telecommunications infrastructure. Temporally, the paper focuses on the current transition period between 2024 and 2026, analyzing the shift from 5G-enabled experimental navigation to the theoretical and emerging 6G-enabled "Internet of Skills." Geographically, the study prioritizes the impact on the Urban-Rural healthcare divide, with a particular focus on how these technologies democratize access to elite spinal expertise in developing healthcare ecosystems. The analysis is limited to spinal surgery, specifically complex deformity corrections and pedicle screw instrumentation, where the high stakes of neurovascular proximity necessitate the sub-millimeter precision offered by AR/VR and robotic assistance.

Furthermore, the paper defines its boundaries through the application of specific qualitative strategic frameworks. It does not aim to provide a quantitative clinical trial or raw surgical data; instead, it utilizes the SWOC (Strengths, Weaknesses, Opportunities, and Challenges) and ABCD (Advantages, Benefits, Constraints, and Disadvantages) frameworks to evaluate the system from a socio-technical and stakeholder-centric perspective. The scope also encompasses a multi-dimensional Impact Analysis, exploring how "Smart" telesurgery influences individuals, communities, and global humanity. By limiting the technical discussion to AR/VR-integrated remote surgery via 5G/6G, the paper maintains a sharp focus on futuristic, technology-oriented super-specializations, excluding traditional open surgeries or non-connected robotic systems.

2. REVIEW OF LITERATURE :

The convergence of immersive visualization and ultra-reliable connectivity represents the most significant paradigm shift in spinal surgery since the introduction of intraoperative fluoroscopy. This review explores the trajectory from training simulations to the current frontier of 6G-enabled remote intervention.

2.1 Historical Context:

The historical development of Extended Reality (XR) in spine surgery has followed two distinct but increasingly intersecting paths: pedagogical simulation and intraoperative guidance. Virtual Reality (VR) was initially adopted as a "flight simulator" for novice residents, providing a reproducible and robust medium for surgical training through high-fidelity simulations (Kuhn et al. (2024). [1]). Studies have shown that VR-based training significantly enhances anatomic knowledge and tactile proficiency before surgeons enter the operating room (MDPI (2024). [11]).

Conversely, Augmented Reality (AR) has evolved from an educational aid into a critical intraoperative adjunct. Early AR applications relied on external workstation monitors, which created a "cognitive attention shift" as surgeons had to look away from the operative field to a screen (Cofano et al. (2021). [5]). The introduction of head-mounted displays (HMDs), such as the **Augmedics' xVision Spine System**, revolutionized this by superimposing CT-based holographic overlays directly onto the patient's anatomy (Burström et al. (2021). [4]). This "heads-up" navigation eliminates the line-of-sight interruption, allowing surgeons to visualize pedicle trajectories through the skin and bone in real-time (Nadeem-Tariq et al. (2023). [2]).

2.2 Connectivity Milestones:

The feasibility of remote telesurgery—performing procedures from a distant master console—has historically been limited by network latency. The **5G epoch** marked the first clinical milestone in this field. In 2019, a landmark series of 12 telerobotic spinal surgeries was performed across six different cities in China, demonstrating that 5G could maintain a stable connection with a mean deviation of only 0.76 ± 0.49 mm between planned and actual positions (Tian et al. (2020). [9]). Despite these successes, 5G networks often face challenges with "haptic-visual desynchronization" when transmitted over transcontinental distances (Misra et al. (2025). [8]).

The theoretical shift to **6G technology** is expected to address these residual barriers by offering sub-millisecond latency (<1ms) and ultra-reliable low-latency communication (URLLC). Current exploratory research suggests that 6G will enable the "Internet of Skills," where haptic feedback (the "feel" of the bone) is transmitted instantaneously, allowing for truly immersive remote interventions (Ding et al. (2025). [6]). This evolution moves the surgical practice from simple "remote operation" to a "borderless digital ecosystem" where specialist expertise is no longer geographically constrained (Jha et al. (2026). [7]).

2.3 Clinical Outcomes:

Clinical evaluation of computer-assisted smart spine surgery (CASS) consistently utilizes the **Gertzbein and Robbins Scale (GRS)** to quantify pedicle screw placement accuracy (Vardiman et al., (2025). [12]). Systematic reviews of AR-assisted procedures report "perfect" accuracy rates (GRS Grade A/B) ranging from 94.1% to 100%, significantly outperforming conventional free-hand techniques which typically range between 80% and 90% (Chandan Reddy et al. (2025). [3]).

Recent clinical trials focusing on scoliosis correction have demonstrated that AR-assisted navigation achieves an overall instrumentation accuracy of 98%, even in cases with severe apical vertebral rotation (Chang et al. (2025). [11]). Furthermore, the technology provides significant safety benefits; studies have documented a **70–90% reduction in intraoperative radiation exposure** for the surgical team, as the need for repeated "confirmation X-rays" is replaced by real-time digital tracking (Zhang et al. (2025). [13]). Beyond intraoperative metrics, emerging data suggests that these precision gains translate into improved long-term patient-reported outcomes, specifically in the Oswestry Disability Index (ODI) scores (Gounine et al. (2025). [14]).

2.4 Keyword-Based Review:

Table 1: Review summary based on the Keyword "Smart Spine Surgery", using Google Scholar search

S. No.	Area	Outcome	Reference
1	'SMART' implantable devices for spinal implants	SMART implants are advanced orthopedic devices that integrate traditional biomechanical strength with sensor-based intelligence to monitor implant performance. Current SMART spinal implants mainly use strain gauges to measure real-time loading, helping detect failures and assess healing by tracking load distribution between bone and implant. Future research aims to correlate this sensor data with clinical outcomes, including complications like pedicle screw loosening and cage subsidence.	Kim, S. J., Wang, T., Pelletier, M. H., & Walsh, W. R. (2022). [15]
2	Smart spine implants	Smart spinal implants enhance healing while providing objective, real-time data on recovery progress. With features like remote monitoring, control, and data analytics, they can improve postoperative care, guide clinical decisions, and reduce complications, offering significant benefits for both patients and surgeons.	Murphy, R. K. (2024). [16]
3	Smart orthopaedic implants	Real-time health monitoring is advancing across medicine, but orthopaedics has lagged in adopting implantable sensor technologies. A deeper understanding of biomechanics, along with integrated sensing, powering, and energy-harvesting solutions, is needed to enable continuous postoperative evaluation. Applying these innovations can drive the development of next-generation smart implants for improved patient monitoring and outcomes.	Ramakrishna, V. A., Chamoli, U., Rajan, G., Mukhopadhyay, S. C., Prusty, B. G., & Diwan, A. D. (2020). [17]
4	Smart implants in orthopedic surgery, improving patient outcomes	Smart implants combine therapeutic and diagnostic functions, offering major potential for improved care and reduced healthcare costs across applications like joint replacement and spine surgery. However, their clinical adoption remains limited due to the need for significant design modifications to integrate sensors. Future progress depends on developing small, simple, and cost-effective sensors that require minimal changes, enabling widespread use of smart implants in routine practice.	Ledet, E. H., Liddle, B., Kradinova, K., & Harper, S. (2018). [18]
5	Sensor based technology applications	Advances in microchip technology have enabled the development of SMART implants across orthopaedics, as highlighted	Viswanathan, V. K., Jain, V. K., Sangani, C.,

	in trauma and orthopaedic surgery	in a review of 30 studies. These sensor-based systems are used in arthroplasty, trauma, spine, paediatric care, infection monitoring, rehabilitation, and sports medicine to support intraoperative guidance and postoperative assessment, including healing, implant stability, and functional recovery.	Botchu, R., Iyengar, K. P., & Vaishya, R. (2023). [19]
6	Emerging Technologies Enhancing ERAS in Spine Surgery	Enhanced Recovery After Surgery (ERAS) in spine surgery improves recovery but faces challenges like limited personalization and adherence. Emerging technologies—such as AI, wearable sensors, remote monitoring, and precision medicine—enable real-time tracking, personalized care, and early complication detection. Although implementation requires validation and cost justification, these innovations have strong potential to enhance patient outcomes and transform postoperative spine care.	Gowd, A. K., Moon, A. S., Shah, R. F., & Kim, T. T. (2025, July). [20]
7	Treating lumbar spinal stenosis patients using smart-shoe technology	About 33% of lumbar spinal stenosis (LSS) patients are dissatisfied after surgery, highlighting the need for better outcome prediction. This study used smart-shoes to capture objective gait data, which showed high accuracy in predicting postoperative disability and pain, outperforming traditional clinical measures. These findings suggest that smart-shoe technology can help identify suitable candidates for surgery and improve treatment planning.	Lee, S. I., Campion, A., Huang, A., Park, E., Garst, J. H., Jahanforouz, N., ... & Lu, D. C. (2017). [21]
8	Intelligence-based spine care model	Musculoskeletal disorders—especially spine-related conditions—are major global causes of disability and healthcare costs, yet effective, standardized care models remain lacking. With rapid technological advances, particularly in artificial intelligence, there is strong potential to transform spine care toward more personalized, efficient, and patient-centered treatment approaches.	Mallow, G. M., Siyaji, Z. K., Galbusera, F., Espinoza-Orías, A. A., Giers, M., Lundberg, H., ... & Samartzis, D. (2021). [22]
9	Smart glasses in spine surgery	This study shows that using smart glasses during fluoroscopy-guided pedicle screw insertion can significantly reduce radiation exposure time and dose without affecting accuracy or procedure time, making it a promising tool for safer spine surgery.	Hiranaka, Y., Takeoka, Y., Yurube, T., Tsujimoto, T., Kanda, Y., Miyazaki, K., ... & Kakutani, K. (2024). [23]
10	The past, present, and future of remote patient monitoring in spine care	Remote patient monitoring (RPM) has evolved into a key component of digital healthcare, enabling real-time data collection and improved clinical decisions. In orthopedics and spine care, emerging tools like wearables and smart implants are transforming patient management, while	Lightsey IV, H. M., Yeung, C. M., Samartzis, D., & Makhni, M. C. (2021). [24]

		also reshaping doctor–patient interactions and raising new considerations around data use and privacy.	
11	Empowering the future of spinal surgery through digital and intelligent technologies	Artificial intelligence is increasingly used in spine surgery for diagnosis, decision-making, navigation, and prognosis, but its clinical utility remains limited due to issues like poor data quality, lack of transparency, and limited real-world application. Improving reliability and effectiveness can enable AI to support comprehensive care across all surgical stages.	Gao, C., Yao, T., Zhang, T., Zhang, W., Wang, J., Zang, F., & Chen, H. (2025). [25]
12	Revolutionizing spine surgery with emerging AI–FEA integration	The integration of artificial intelligence and finite element analysis (FEA) is transforming spine surgery by enabling precise planning, real-time surgical guidance, and accurate outcome prediction. Together, they support personalized treatment, improve surgical safety, and enhance recovery monitoring, driving a shift toward data-driven and precision-based spine care.	Franceschini, C., Ahmadi, M., Zhang, X., Wu, K., Lin, M., Weston, R., ... & Vrionis, F. D. (2025). [26]
13	Advancing Spine Surgery	Spine surgery is evolving through the integration of spatial computing, artificial intelligence, and advanced imaging, enhancing diagnosis, planning, surgical precision, and postoperative care. While these technologies enable more personalized and accurate treatment, challenges such as validation, cost, and ethical concerns must be addressed to fully realize their potential.	Elsayed, G. A., Dykhouse, G., Ikwuegbuenyi, C. A., Willett, N., Hussain, I., Hamad, M., ... & Härtl, R. (2025). [27]

Table 2: Review summary based on the Keyword “AR/VR Technology in spine surgery” using Google scholar search

S. No.	Area	Outcome	Reference
1	Virtual and augmented reality in spine surgery	Augmented and virtual reality technologies are increasingly used in spine surgery for training, planning, and intraoperative guidance, improving accuracy and reducing radiation exposure. While they show strong potential to transform surgical practice, further advancements and standardized requirements are needed for broader clinical adoption.	McCloskey, K., Turlip, R., Ahmad, H. S., Ghenbot, Y. G., Chauhan, D., & Yoon, J. W. (2023). [28]
2	The development and applications of augmented and virtual reality technology in spine surgery training	The COVID-19 pandemic accelerated interest in augmented and virtual reality for spine surgery training, but current evidence remains limited and methodologically varied. While these technologies show promise, further high-quality, multi-center studies are needed to validate their effectiveness and support wider adoption.	Jung, Y., Muddaluru, V., Gandhi, P., Pahuta, M., & Guha, D. (2024). [29]

3	Augmented reality and virtual reality in spine surgery	Virtual reality and augmented reality are emerging as transformative healthcare technologies, with VR offering fully immersive, computer-generated environments enhanced by sensory and interactive feedback. These innovations enable realistic simulation and interaction, advancing medical training and healthcare delivery.	Judy, B. F., Menta, A., Pak, H. L., Azad, T. D., & Witham, T. F. (2024). [30]
4	Utility of augmented reality and virtual reality in spine surgery	Augmented, virtual, and mixed reality technologies are emerging tools in spine surgery, showing promising results in improving surgical accuracy, outcomes, and reducing complications. Although current clinical data are limited, early evidence supports their effectiveness and safety in enhancing spine surgical procedures.	Sumdani, H., Aguilar-Salinas, P., Avila, M. J., Barber, S. R., & Dumont, T. (2022). [31]
5	Improvisation in spinal surgery using AR (augmented reality), MR (mixed reality), and VR (virtual reality)	Advancements in extended reality technologies (AR, VR, MR) are increasingly enhancing spine surgery through applications in education, training, preoperative planning, and surgical precision, especially in minimally invasive procedures. These technologies offer significant potential to improve outcomes and provide a framework for broader clinical adoption and stakeholder value.	Garg, D., Dubey, N., Goel, P., Ramoliya, D., Ganatra, A., & Kotecha, K. (2024). [32]
6	Applications of augmented and virtual reality in spine surgery and education	As spine surgery becomes more complex and minimally invasive, technologies like augmented reality and virtual reality enhance surgical visualization and training. AR overlays real-time anatomical guidance during procedures, while VR enables immersive simulation for skill development, improving precision and education in spine surgery.	Fourman, M. S., Ghaednia, H., Lans, A., Lloyd, S., Sweeney, A., Detels, K., ... & Schwab, J. H. (2021, [33]
7	Current innovation in virtual and augmented reality in spine surgery	In spine surgery, precise instrumentation and proper patient selection are critical, especially with the rise of minimally invasive techniques. Advanced visualization tools like augmented, virtual, and mixed reality improve surgical accuracy and training, with AR aiding real-time procedures and VR/MR supporting simulation and preparation.	Yuk, F. J., Maragkos, G. A., Sato, K., & Steinberger, J. (2021). [34]
8	Virtual and augmented reality in spine surgery	Virtual and augmented reality are transforming spine surgery by enhancing training and improving surgical precision, though their adoption is limited by cost and integration challenges. Ensuring reliability, validation, and cost-effectiveness will be key to their broader use and future impact in healthcare.	Hasan, S., Miller, A., Higginbotham, D., Saleh, E. S., McCarty, S., & Miller, A. K. (2023). [35]
9	Augmented, virtual and mixed reality in spinal surgery	Augmented, virtual, and mixed reality technologies are emerging tools in spine surgery, improving precision and guidance, especially in minimally invasive procedures. Although promising, their widespread adoption depends on proven safety, effectiveness, and cost-efficiency.	Sakai, D., Joyce, K., Sugimoto, M., Horikita, N., Hiyama, A., Sato, M., ... & Watanabe, M. (2020). [36]

10	Virtual, augmented, and mixed reality applications for surgical rehearsal, operative execution, and patient education in spine surgery	Advances in VR, AR, and MR technologies are expanding their use in spine surgery, with VR mainly supporting training and education, and AR/MR enhancing surgical precision. While evidence shows promising applications, especially in procedures like pedicle screw placement, these technologies are still evolving as effective tools in clinical practice.	Bui, T., Ruiz-Cardozo, M. A., Dave, H. S., Barot, K., Kann, M. R., Joseph, K., ... & Molina, C. A. (2024). [37]
11	Augmented reality and virtual reality transforming spinal imaging landscape	Augmented and virtual reality technologies in spinal navigation show promising accuracy and scalability, with growing clinical relevance. However, further research and economic validation are needed to address challenges and support wider adoption among healthcare stakeholders.	Shelke, Y., & Chakraborty, C. (2020). [38]
12	Integrating augmented reality in spine surgery	Augmented reality is transforming spine surgery by providing immersive 3D visualization that improves surgical precision, planning, and outcomes while reducing invasiveness and operative time. Despite challenges like technical limitations and learning curves, AR shows strong potential in surgery, education, and patient care, marking a significant advancement in clinical practice.	De Jesus Encarnacion Ramirez, M., Chmutin, G., Nurmukhametov, R., Soto, G. R., Kannan, S., Piavchenko, G., ... & Montemurro, N. (2024). [39]
13	The Role of Augmented Reality and Virtual Reality in Contemporary Spine Surgery	The Lippincott Continuing Medical Education Institute, accredited by the Accreditation Council for Continuing Medical Education, offers up to 1.5 AMA PRA Category 1 Credits™ for this activity. Physicians must read the article and score at least 70% on the quiz and evaluation to earn credit.	Steinberger, J., & Qureshi, S. (2020). [40]
14	Advances in Spinal Surgery: 3D Printing, Augmented Reality and Artificial Intelligence	Spine surgery is undergoing a technological transformation driven by 3D printing, augmented reality, and artificial intelligence, enhancing implants, surgical navigation, and personalized care. These innovations are improving outcomes across all stages of treatment and are expected to further advance precision and efficiency in spine care.	Yahanda, A. T., Krishnan, A., Joseph, K., & Molina, C. A. (2026). [41]

3. OBJECTIVES OF THE PAPER :

The following strategic objectives are identified for this scholarly research analysis

(1) **To evaluate the technical feasibility of 6G-enabled remote AR spine surgery:** To systematically examine the transition from 5G to 6G and its role in providing the sub-millisecond latency (<1ms) and ultra-reliable connectivity required for high-precision neurovascular spinal interventions.

(2) **To analyze the integration of AR/VR as a diagnostic and navigational tool:** To explore how holographic 3D anatomical registration and "X-ray vision" overlays enhance the surgeon's accuracy beyond the capabilities of the human eye and traditional fluoroscopy.

(3) **To investigate the systemic impact of remote telesurgery on global healthcare equity:** To assess how 6G-connected "Smart" surgery can democratize access to elite spinal expertise, potentially bridging the urban-rural healthcare divide through "borderless" surgical services.

(4) **To identify and categorize technological and infrastructural barriers:** To explore the "Latency-Haptic Perception Gap" and other systemic challenges, such as cybersecurity risks and the requirement for specialized high-speed network infrastructure.

(5) **To perform a multi-framework strategic analysis (SWOC):** To evaluate the internal **Strengths and Weaknesses** (e.g., precision vs. high cost) and external **Opportunities and Challenges** (e.g., global collaboration vs. regulatory hurdles) of adopting this tech-stack.

(6) **To assess value propositions through ABCD Stakeholder Analysis:** To determine the practical **Advantages, Benefits, Constraints, and Disadvantages** for key stakeholders including surgeons, patients, hospitals, and telecommunication providers.

(7) **To evaluate societal readiness and ethical implications:** To investigate the impact of automated and remote surgical systems on society and humanity, addressing concerns such as medical liability in network failures and the potential "de-skilling" of local practitioners.

4. RESEARCH METHODOLOGY :

The research methodology for this scholarly article follows a **qualitative and exploratory research design**. This approach is specifically chosen to investigate the emerging ethical, technological, and systemic dimensions of computer-assisted spine surgery and 6G-enabled telesurgery. By focusing on "how" and "why" these futuristic technologies impact surgical precision and global healthcare equity, this design allows for the identification of core themes and a comprehensive psychological and ethical mapping of the field [42-45].

The data collection process integrates traditional academic rigor with modern, **AI-augmented qualitative inquiry**. Primary data is derived from a systematic review of extant literature, including peer-reviewed journals, medical white papers, and 6G patent filings sourced from repositories such as Google Scholar. This traditional search is further enriched through **"Expert Opinion Synthesis"** using specifically engineered prompts within AI-driven Large Language Models (GPTs). This hybrid approach ensures that the analysis captures both established clinical outcomes and the most recent theoretical shifts in high-speed connectivity [46-49].

To ensure a multi-faceted evaluation, the synthesized information is subjected to a rigorous analysis using three distinct strategic frameworks: **SWOC, ABCD, and Impact Analysis**. The **SWOC framework** (Strengths, Weaknesses, Opportunities, and Challenges) is justified as a tool to evaluate the functional utility and internal strategic advantages of the surgical system. The **ABCD model** (Advantages, Benefits, Constraints, and Disadvantages) is utilized to deconstruct the value proposition from diverse stakeholder perspectives, including patients, families, and medical institutions. Finally, **Impact Analysis** is employed to assess the nested scales of influence—ranging from individual surgeon resilience to the broader implications for community health and global humanity.

5. THE "SMART" ECOSYSTEM (TECHNICAL DEEP DIVE) :

The realization of remote spinal intervention requires a sophisticated integration of immersive visualization, robotic precision, and ultra-low-latency communication. This section deconstructs the technical architecture that enables a "borderless" surgical environment.

5.1 AR/VR in Spinal Care:

The integration of Augmented Reality (AR) and Virtual Reality (VR) represents a shift from 2D monitor-based navigation to a 3D immersive experience. **3D anatomical registration** is the foundational step, where preoperative CT or MRI data is mapped onto the patient's physical body using optical tracking or surface recognition (Burström et al. (2021). [4]). Once registered, **holographic overlays** are projected onto the surgeon’s Head-Mounted Display (HMD), providing "X-ray vision" that reveals pedicle trajectories and neurovascular structures directly through the soft tissue (Nadeem-Tariq et al. (2025). [2]). To bridge the sensory gap, **haptic feedback loops** are integrated into the surgical instruments, allowing the surgeon to "feel" the bone density and mechanical resistance of the vertebrae, which is critical for preventing cortical wall breaches (Bui et al. (2024). [50]). This sensory trifecta—visual, spatial, and tactile—minimizes the cognitive load and significantly enhances instrumentation accuracy (Cofano et al., 2025). [5]).

5.2 Remote Telesurgery:

The telesurgical framework is divided into two distinct but synchronized nodes. The **Remote Surgeon Console (Master)** serves as the human-interface node, equipped with high-definition 3D displays and haptic controllers that capture the surgeon's hand movements with sub-millimeter precision (Ding et al. (2025). [6]). Conversely, the **Patient Side Robot (Slave)** is located in the operating theater, consisting of specialized robotic arms that translate the master's inputs into physical actions on the patient's spine (Tian et al. (2020). [9]). This architecture must maintain a "transparent" connection, where the robotic system filters out physiological tremors while ensuring that the surgeon retains full agency over the procedure (Jha et al. (2026). [7]). Recent advancements in **telerobotic spinal systems** have demonstrated that this master-slave configuration can successfully execute complex tasks like laminectomies and pedicle screw fixation across vast geographical distances (Misra et al. (2026). [8]).

5.3 The Connectivity Backbone:

The "bottleneck" of telesurgery is the network's ability to transmit high-fidelity data without lag. While **5G technology** was a major milestone, providing bandwidth up to 10 Gbps and reducing latency to the 20–50 millisecond range, it still faces challenges with "jitter" during transcontinental transmissions (Tian et al. (2020). [9]). **6G technology** is emerging as the definitive solution, targeting **sub-millisecond latency (<1ms)** and a reliability rate of 99.99999% (Ding et al. (2025). [6]). While 5G supports the "Internet of Things," 6G is designed for the **"Internet of Skills,"** where massive bandwidth (up to 1 Tbps) allows for the real-time transmission of multi-sensory data, including holographic video and 4D haptic sensations (Jha et al. (2026). [7]). This shift ensures that the "latency-haptic perception gap" is eliminated, making the remote experience indistinguishable from local surgery (Chandan Reddy et al. (2025). [3]).

Table 3: Comparison of Connectivity backbone

Feature	**5G (Current Standard)**	**6G (Emerging Target)**
Peak Data Rate	10 – 20 Gbps	100 Gbps – 1 Tbps
End-to-End Latency	5 – 20 ms	< 1 ms
Reliability	99.999%	99.99999%
Surgical Utility	Remote Navigation/Slow Tasks	High-Speed Active Intervention

6. ANALYSIS USING SWOC FRAMEWORK :

6.1 About the SWOC Analysis:

The **SWOC analysis framework**—representing Strengths, Weaknesses, Opportunities, and Challenges—is a globally recognized strategic tool used to systematically evaluate the overall position and environment of a concept, system, or organization. As a foundational methodology for qualitative exploratory research, it enables a multi-dimensional assessment by identifying internal factors that can be controlled (Strengths and Weaknesses) and external variables beyond immediate control (Opportunities and Challenges) (Aithal & Kumar (2015). [51]). The primary utility of the SWOC model lies in its ability to facilitate structured thinking, allowing strategists to align a system's internal capabilities with the requirements of its external landscape to ensure long-term sustainability and goal achievement. While traditionally applied in business, modern adaptations have expanded its scope to include the evaluation of individual performance, educational institutions, and complex technological systems. By bridging the gap between theoretical potential and practical application, the framework serves as a critical diagnostic instrument for strategy formulation, corrective action planning, and performance optimization in the 21st century. Ultimately, when integrated with other methodologies like the ABCD analysis (Advantages, Benefits, Constraints, and Disadvantages), SWOC provides a holistic perspective necessary for navigating dynamic environments and maximizing strategic output [52-58].

6.2 SWOC Analysis of Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G:

6.2.1 Strengths of Smart Spine Surgery via 5G/6G & AR/VR:

In a **SWOC analysis** (Strengths, Weaknesses, Opportunities, and Challenges), "Strengths" represent the internal positive attributes and core competencies of a technological framework. For **Computer-Assisted Smart Spine Surgery via 5G/6G and AR/VR**, these strengths center on precision, safety, and the removal of geographical barriers.

Table 4: Strengths of Smart Spine Surgery via 5G/6G & AR/VR

S. No.	Key Strengths	Description
1	**Enhanced Surgical Precision**	AR-assisted platforms provide high-fidelity 3D anatomical overlays that significantly increase the accuracy of pedicle screw placement compared to traditional free-hand techniques (Bui et al. (2024). [50]).
2	**Reduction in Radiation Exposure**	Real-time digital navigation reduces the need for frequent intraoperative fluoroscopy, protecting both the patient and the surgical team from ionizing radiation (Nadeem-Tariq et al. (2025). [2]).
3	**Ultra-Low Latency for Real-Time Feedback**	The shift from 5G to 6G technology targets sub-millisecond latency, enabling near-instantaneous synchronization between the remote surgeon's actions and robotic execution (Ding et al. (2025). [6]).
4	**Improved Spatial Visualization**	Wearable head-mounted displays (HMDs) allow surgeons to maintain a continuous line of sight on the surgical field while viewing internal structures holographically (Cofano et al., 2021). [5]).
5	**Democratization of Expert Surgical Care**	High-speed connectivity enables elite specialists to perform or supervise complex procedures in rural or underserved regions from a distant remote console (Jha et al. (2026). [7]).
6	**Optimized Surgical Workflow**	Smart navigation systems streamline operative steps by providing real-time trajectory guidance and reducing the cognitive load required to interpret 2D imaging (Burström et al. (2021). [4]).
7	**Haptic Immersion for Tactile Safety**	Advanced feedback systems transmit the "feel" of bone resistance to the remote surgeon, allowing for safer manipulation near delicate neurovascular structures (Ding et al. (2025). [6]).
8	**Minimized Operative Time**	Preoperative 3D planning integrated with robotic guidance often leads to faster instrumentation placement and reduced overall surgical duration (Bui et al. (2024). [50]).
9	**Reduced Postoperative Complications**	Increased accuracy in complex reconstructions results in lower rates of screw misplacement, fewer revisions, and improved long-term patient-reported outcomes (Chandan Reddy et al. (2025). [3]).
10	**High Fidelity Surgical Training**	VR-based simulations offer a risk-free, reproducible environment for trainees to master intricate spinal procedures before entering a live operating theater (Kuhn et al. (2024). [1]).

6.2.2 Weaknesses of Smart Spine Surgery via 5G/6G & AR/VR:

In a **SWOC analysis** (Strengths, Weaknesses, Opportunities, and Challenges), "Weaknesses" represent the internal limitations and operational vulnerabilities of a technological system. For **Computer-Assisted Smart Spine Surgery via 5G/6G and AR/VR**, these weaknesses primarily stem from the high barriers to entry, technical complexities, and human-factor constraints.

Table 5: Weaknesses of Smart Spine Surgery via 5G/6G & AR/VR

S. No.	Key Weaknesses	Description
1	**Exorbitant Implementation Costs**	The substantial capital required for robotic hardware, AR/VR equipment, and high-speed network infrastructure often makes

		the technology prohibitive for smaller healthcare settings. (Ding et al. (2025). [6]).
2	**Steep Learning Curve for Surgeons**	Mastering the integration of robotic navigation and AR interfaces requires extensive specialized training, which may initially lead to longer operative times and increased surgeon fatigue (Nadeem-Tariq et al. (2025). [2]).
3	**Potential for Technical Malfunctions**	The high complexity of these systems introduces risks of software glitches, hardware failures, or sensor malfunctions that could compromise surgical precision (Cofano et al., 2021). [5]).
4	**Loss of Direct Tactile Sensation**	Surgeons operating via robotic arms often face a reduction in "haptic feel," making it difficult to perceive subtle tissue resistances without highly advanced feedback systems (Jha et al. (2026). [7]).
5	**Extended Setup and Preparation Time**	The need for precise calibration of robotic instruments and registration of AR holographic models can significantly increase preoperative time (Bui et al. (2024). [50]).
6	**Dependency on Constant High-Bandwidth Connectivity**	Effective telesurgery requires a minimum bandwidth—often exceeding 150 Mbps—making the system vulnerable to any degradation in network performance (Kuhn et al. (2024). [1]).
7	**Cybersecurity Vulnerabilities**	Telesurgery systems are susceptible to cyber threats, including Denial-of-Service (DoS) attacks and data breaches, which pose direct risks to patient safety during live procedures (Nadeem-Tariq et al. (2025). [2]).
8	**Ergonomic Constraints of AR Hardware**	The physical weight and heat generation of current Head-Mounted Displays (HMDs) can cause discomfort and distraction for surgeons during long-duration procedures. (Tian et al. (2020). [9]).
9	**Cumulative Radiation Risks from Registration**	While intraoperative radiation is reduced during the procedure, the high-resolution CT scans required for initial 3D registration can elevate the patient's lifetime cancer risk (Bui et al. (2024). [50]).
10	**Incompatibility with Complex Anatomical Variations**	Current robotic systems may struggle to adapt to severe spinal deformities or cases with extensive scar tissue from revision surgeries (Li et al. (2026). [10]).

6.2.3 Opportunities of Smart Spine Surgery via 5G/6G & AR/VR:

In a **SWOC analysis** (Strengths, Weaknesses, Opportunities, and Challenges), "Opportunities" refer to the external favourable factors that a system can exploit to gain a competitive advantage or achieve transformative growth. For **Computer-Assisted Smart Spine Surgery via 5G/6G and AR/VR**, these opportunities lie in global connectivity, artificial intelligence integration, and the democratization of surgical expertise.

Table 6: Opportunities of Smart Spine Surgery via 5G/6G & AR/VR

S. No.	Key Opportunities	Description
1	**Elimination of Geographical Health Disparities:**	The high-speed connectivity of 5G and 6G allows world-class spinal surgeons to provide remote care to patients in geographically isolated or rural areas, significantly improving global healthcare equity (Jha et al. (2026). [7]).
2	**Synergy with Artificial Intelligence (AI)**	The integration of AI with AR can enable real-time automated segmentation and predictive navigation, helping surgeons identify "safe zones" during complex deformity corrections (Bui et al. (2024). [50]).

3	**Global Collaborative "Hub-and-Spoke" Models**	High-bandwidth networks facilitate dual-console telesurgery, where multiple experts across different continents can collaborate on a single live spinal procedure (Li et al. (2026). [10]).
4	**Advancement in Personalized 3D-Printed Implants**	Combining AR navigation with 3D bioprinting offers the opportunity to create and precisely place patient-specific titanium cages tailored to unique anatomical dimensions (Lewandrowski et al. (2024). [59]).
5	**Democratization of Surgical Education**	Open-source 3D-printed models combined with remote VR guidance provide a scalable, low-cost platform for training neurosurgical residents in developing nations (Li et al. (2026). [10]).
6	**Real-Time "Digital Twin" Simulation**	The massive data rates of 6G allow for the creation of a "Digital Twin" of the patient's spine that responds in real-time to surgical maneuvers, allowing for "what-if" testing during surgery (Jha et al. (2026). [7]).
7	**Integration of "Internet of Skills" Haptics**	Future 6G networks can support the instantaneous transmission of multi-sensory haptic data, enabling a true tactile "Internet of Skills" for remote spinal palpation (Ding et al. (2025). [6]).
8	**Disaster and Emergency Response Capability**	Mobile surgical units equipped with 5G/6G can be deployed to disaster zones, allowing remote specialists to perform life-saving spinal stabilization procedures on-site (Xie et al. (2025). [60]).
9	**Reduction in Global Surgical Backlogs**	By optimizing the allocation of surgical resources through telerobotics, healthcare systems can reduce the massive waitlists for elective spinal surgeries (Li et al. (2026). [10]).
10	**Enhanced Patient Communication and Consent**	AR technology can be used to project a 3D model of the surgical plan for patients, significantly improving their understanding of the procedure and clinical outcomes (Bui et al. (2024). [50]).

6.2.4 Challenges of Smart Spine Surgery via 5G/6G & AR/VR:

In a **SWOC analysis** (Strengths, Weaknesses, Opportunities, and Challenges), "Challenges" represent external threats or environmental barriers that could hinder the successful implementation of a system. For **Computer-Assisted Smart Spine Surgery via 5G/6G and AR/VR**, these challenges involve high-level regulatory, technical, and ethical hurdles.

Table 7: Challenges of Smart Spine Surgery via 5G/6G & AR/VR

S. No.	Key Challenges	Description
1	**Lack of Global Regulatory Uniformity**	The absence of a unified international framework creates massive legal uncertainty regarding jurisdiction and licensing for cross-border remote surgeries (Elendu et al. (2024). [61]).
2	**Liability and Malpractice Ambiguity**	Determining legal responsibility becomes exceptionally complex in cases of surgical complications where the failure could be attributed to the surgeon, the robot, or the network provider (Saceanu et al. (2015). [62]).
3	**Network Jitter and Latency Spikes**	Even with 6G, the potential for "jitter" (variation in delay) during transcontinental data transmission can lead to desynchronized haptic and visual feeds, endangering patient safety (Misra et al. (2025). [8]).
4	**Sophisticated Cyber-Physical Attacks**	Malicious actors could perform "man-in-the-middle" attacks to manipulate robotic movements or obstruct surgical commands in real-time (Punitha et al. (2025). [63]).
5	**Ethical Concerns of Dehumanization**	The physical distance inherent in telesurgery may erode the traditional surgeon-patient relationship, leading to a perceived

		"objectification" of the patient as a digital data set (Lewandrowski et al. (2024). [59])
6	**Interoperability Gaps Between Platforms**	The current lack of standardized communication protocols between different AR headsets and robotic systems limits the integration of a seamless "Smart" ecosystem (Deshmukh et al. (2021). [64]).
7	**Informed Consent Challenges**	Effectively explaining the specific risks of network failure or remote robotic malfunction to patients remains a significant ethical and communication hurdle (Elendu et al. (2024). [61]).
8	**High Technological Obsolescence Rates**	The rapid evolution from 5G to 6G and emerging AR hardware may lead to high institutional costs for constant equipment updates and software patches (Bui et al. (2024). [50]).
9	**Algorithmic Bias in AI Navigation**	Automated "Smart" navigation systems may suffer from biases in their training data, potentially leading to lower accuracy in patients with rare anatomical variations (Agrawal (2018). [65]).
10	**Global Digital Divide**	There is a persistent risk that these futuristic technologies will only benefit high-resource nations, further widening the gap in healthcare quality between developed and developing countries (Jha et al. (2026). [7]).

7. ABCD STAKEHOLDERS ANALYSIS FRAMEWORK :

7.1 About ABCD Analysis from the Stakeholders' perspective:

The **ABCD analysis framework** is a robust qualitative and semi-quantitative research methodology designed to evaluate a business model, concept, or strategy by deconstructing it into four distinct dimensions: **Advantages, Benefits, Constraints, and Disadvantages** (Aithal et al., (2015). [66]). When applied from a stakeholders' perspective, the framework serves as a critical diagnostic tool to identify the value proposition and operational hurdles associated with a specific system (Aithal (2016). [67]). The "Advantages" and "Benefits" categories focus on the positive attributes and long-term gains for various groups, such as surgeons, patients, and healthcare institutions, while the "Constraints" and "Disadvantages" highlight the systemic limitations and potential negative outcomes. This stakeholder-centric approach is particularly effective in exploratory research, as it allows for a nuanced understanding of how a technological shift, such as 6G-enabled telesurgery, impacts individual users and society at large. By utilizing the ABCD technique, researchers can systematically map the interests of diverse actors, ensuring that the strategic implementation of a system balances technological innovation with ethical and practical viability. Ultimately, this analysis provides a holistic view that assists policymakers and strategists in optimizing the "Benefits" while proactively mitigating the "Constraints" of the proposed idea or system. ABCD analysis technique has the following four formats: (i) ABCD Listing from author's perspective [68-147], (ii) ABCD Listing from Stakeholders' perspectives [148 -170], (iii) ABCD Factor and Elemental Analysis [171-176], and (iv) ABCD quantitative and empirical analysis [177 – 197]. In this section, ABCD analysis of Chapter 18 of the Bhagavad Gita is done from the stakeholders’ Perspectives.

7.2 Advantages of Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G from the Stakeholders' perspective:

In the **ABCD analysis framework**, "Advantages" represent the systemic positive characteristics and inherent strengths of the technology from the perspective of various stakeholders, including surgeons, healthcare administrators, and technology providers (Aithal et al., (2015). [66]). For **Computer-Assisted Smart Spine Surgery**, these advantages focus on the superior technical capabilities afforded by the integration of AR/VR and 6G connectivity.

Table 8: Advantages of Smart Spine Surgery via 5G/6G & AR/VR from Stakeholders' Perspective

S. No.	Key Advantages	Description
1	**Sub-millimeter Surgical Accuracy**	The integration of AR holographic overlays allows surgeons to achieve unprecedented precision in pedicle screw placement,

		minimizing the risk of neurological injury (Burström et al. (2021). [4]).
2	**Zero-Latency Remote Manipulation**	The transition to 6G infrastructure provides the ultra-low latency required for real-time synchronization between the remote expert's console and the patient-side robot (Ding et al. (2025). [6]).
3	**Enhanced Intraoperative Visualization**	Head-mounted displays provide stakeholders with a "heads-up" display, allowing surgeons to maintain their natural line of sight while viewing internal spinal structures (Nadeem-Tariq et al. (2025). [2]).
4	**Significant Radiation Mitigation**	The use of digital 3D registration reduces the reliance on repetitive X-ray imaging, creating a safer occupational environment for the entire surgical team (Chandan Reddy et al. (2025). [3]).
5	**Seamless Global Collaboration**	High-speed networks enable real-time tele-mentoring and dual-console surgery, allowing experts to assist in complex cases from different geographical hubs (Jha et al. (2026). [7]).
6	**Optimized Ergonomics for Surgeons**	Robotic consoles allow surgeons to operate from a seated, ergonomic position, reducing the physical strain and fatigue associated with long-duration spinal reconstructions (Cofano et al. (2025). [5]).
7	**High-Fidelity Haptic Feedback**	Advanced sensors in the "Smart" ecosystem provide remote stakeholders with tactile sensations of bone density, replicating the feel of open surgery (Ding et al. (2025). [6]).
8	**Automated Surgical Planning**	AI-driven software within the AR environment can automatically suggest optimal screw trajectories based on the patient's unique spinal morphology (Bui (2024). [50]).
9	**Efficient Resource Allocation**	Telesurgery allows hospitals to utilize elite surgical talent across multiple facilities without the need for physical travel, optimizing specialist availability (Misra et al., (2026). [8]).
10	**Risk-Free Procedural Rehearsal**	VR environments allow surgical teams to practice the specific steps of a complex deformity correction on a patient-specific digital twin before the actual incision (Kuhn et al., (2024). [1]).

7.3 Benefits of Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G from the Stakeholders' perspective:

In the **ABCD analysis framework**, "Benefits" refer to the long-term, value-added outcomes and positive results that stakeholders experience as a consequence of using the system (Aithal et al. (2015). [66]). For **Computer-Assisted Smart Spine Surgery**, these benefits extend beyond mere technical advantages to include economic efficiency, improved quality of life, and global health transformation.

Table 9: Benefits of Smart Spine Surgery via 5G/6G & AR/VR from Stakeholders' Perspective

S. No.	Key Benefits	Description
1	**Accelerated Postoperative Recovery**	Enhanced precision in minimally invasive spinal procedures leads to reduced muscle trauma and faster return to daily activities for patients (Chandan Reddy et al., (2025). [3]).
2	**Increased Hospital Bed Turnover**	Reduced surgical complications and shorter inpatient stays allow healthcare institutions to optimize resource utilization and treat more patients (Misra et al. (2026). [8]).
3	**Extended Professional Longevity for Surgeons**	The use of ergonomic robotic consoles reduces the physical toll and "surgeon burnout" caused by traditional, physically demanding spine surgeries (Cofano et al. (2025). [5]).
4	**Mitigation of Geographical Healthcare Disparities**	Remote telesurgery benefits rural communities by providing access to specialized spinal care without the need for expensive patient transfers (Jha et al. (2026). [7]

5	**Substantial Long-term Cost Savings**	While initial costs are high, the reduction in revision surgeries and infection rates provides significant long-term financial benefits to insurance providers and patients (Nadeem-Tariq et al. (2023). [2]).
6	**Enhanced Clinical Training Outcomes**	VR-based curricula provide a standardized, high-quality educational benefit for residents, ensuring competency before they perform live procedures (Kuhn et al. (2024). [1]).
7	**Data-Driven Surgical Refinement**	The digital nature of "Smart" surgery allows for the continuous collection of performance data, benefiting the medical community through large-scale clinical research (Ding et al. (2025). [6]).
8	**Improved Patient Psychological Well-being**	The use of AR for preoperative visualization increases patient confidence and reduces anxiety regarding complex spinal interventions (Bui (2024). [50]).
9	**Prevention of Occupational Health Hazards**	Significantly lower radiation exposure benefits the long-term health and safety of surgical staff, reducing the risk of radiation-induced illnesses (Chandan Reddy et al. (2025). [3]).
10	**Enhanced Precision in Complex Deformities**	Advanced navigation offers life-changing benefits for patients with severe scoliosis or kyphosis by achieving corrections previously considered too high-risk (Burström et al., (2021). [4]).

7.4 Constraints of Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G from the Stakeholders' perspective:

In the **ABCD analysis framework**, "Constraints" represent the structural and operational limitations that restrict the system from reaching its full potential, often serving as the primary barriers for stakeholders like hospital administrators and network engineers (Aithal et al. (2015). [66]). For **Computer-Assisted Smart Spine Surgery**, these constraints are primarily centered on infrastructure, high-fidelity data requirements, and current hardware limitations.

Table 10: Constraints of Smart Spine Surgery via 5G/6G & AR/VR from Stakeholders' Perspective

S. No.	Key Constraints	Description
1	**High Initial Capital Outlay**	The extreme cost of acquiring 6G-ready robotic systems and AR infrastructure remains a significant financial constraint for most public and private healthcare facilities (Nadeem-Tariq et al. (2025). [2]).
2	**Network Bandwidth Requirements**	Remote spine surgery requires a massive, consistent bandwidth to handle real-time 3D holographic streaming without data packet loss (Misra et al. (2026). [8]).
3	**Haptic Fidelity Limitations**	Current robotic systems struggle to perfectly replicate the nuanced "tactile feel" of cortical bone versus soft tissue during remote operations (Ding et al. (2025). [6]).
4	**Hardware Portability and Ergonomics**	The bulky nature of current AR headsets can lead to physical discomfort and restricted movement for surgeons during lengthy reconstructive procedures (Cofano et al. (2021). [5]).
5	**Lack of Universal Interoperability**	A major constraint for hospital stakeholders is the inability to seamlessly integrate different brands of navigation software with various robotic arms (Deshmukh (2021). [64]).
6	**Need for Specialized Technical Support**	Operating these systems requires an on-site team of specialized biomedical and network engineers, increasing the human resource burden (Liv Hospital (2026). [198]).
7	**Data Processing Latency**	Even with high speeds, the computational time required to render 3D holographic overlays from CT data can create minor but noticeable visual lag (Nadeem-Tariq et al. (2023). [2]).

8	**Cybersecurity Infrastructure**	Stakeholders must invest in complex end-to-end encryption and "firewall-in-surgery" protocols to prevent unauthorized access to live robotic controls (Punitha (2025). [63]).
9	**Regulatory Licensing Barriers**	The lack of cross-state or cross-border medical licensing for remote surgeons restricts the geographical utility of telesurgery (Elendu et al. (2024). [61]).
10	**Battery and Power Management**	The limited battery life of wireless AR headsets necessitates frequent charging or tethering, which can interfere with the sterile surgical field (Nadeem-Tariq et al. (2025). [2]).

7.5 Disadvantages of Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G from the Stakeholders' perspective:

In the **ABCD analysis framework**, "Disadvantages" represent the potential negative consequences, ethical dilemmas, and systemic drawbacks that stakeholders may encounter following the adoption of a new system (Aithal et al., (2015). [66]). For **Computer-Assisted Smart Spine Surgery**, these disadvantages highlight the risks of dehumanized care, legal instability, and the widening of the global digital healthcare gap.

Table 11: Disadvantages of Smart Spine Surgery via 5G/6G & AR/VR from Stakeholders' Perspective

S. No.	Key Disadvantages	Description
1	**Increased Risk of Medico-Legal Ambiguity**	The lack of clear legal frameworks for remote surgery creates significant liability risks for stakeholders in the event of technical or human error (Saceanu et al. (2015). [62]).
2	**Potential for "De-skilling" of Local Surgeons**	Over-reliance on robotic assistance and remote experts may lead to a decline in the traditional tactile surgical skills of local practitioners (Misra et al. (2025). [8]).
3	**Dehumanization of the Surgeon-Patient Relationship**	The physical distance inherent in telesurgery can lead to a perceived loss of empathy and a "mechanical" view of the patient (Elendu et al. (2024). [61]).
4	**Vulnerability to Lethal Cyber-Physical Attacks**	Malicious interference with the surgical network can result in unauthorized robotic movements, posing a direct threat to the patient's life (Punitha (2022). [63]).
5	**Widening of the Global Healthcare Divide**	The extreme cost and infrastructure requirements ensure that only wealthy urban centers benefit, further disadvantaging rural and low-income populations (Jha et al. (2026). [7]).
6	**Psychological Stress of "Latency Anxiety"**	Remote surgeons may experience significant cognitive stress and "performance anxiety" due to the constant fear of network lag or disconnection (Misra et al. (2026). [8]).
7	**Environmental Impact of Rapid Technological Obsolescence**	The fast-paced evolution of 6G and AR hardware leads to frequent equipment replacement and the accumulation of specialized electronic medical waste (Bui et al. (2024). [50]).
8	**Compromised Patient Data Privacy**	The massive transfer of real-time 3D anatomical data over public and private clouds increases the risk of sensitive medical data breaches (Punitha et al. (2022). [63]).
9	**High Maintenance and Subscription Burdens**	Beyond the initial purchase, stakeholders face ongoing high costs for software licensing and proprietary technical support (Nadeem-Tariq et al. (2025). [2]).
10	**Ethical Dilemmas in Resource Allocation**	Investing heavily in "Smart" surgery may divert essential funds away from basic primary healthcare and preventative spinal medicine (Elendu et al. (2024). [61])

8. TECHNOLOGY & IMPACT ANALYSIS :

The integration of 6G-enabled AR/VR into spinal surgery represents a socio-technical transformation that extends far beyond technical precision. This section evaluates the readiness of these technologies and their multi-scaled consequences for individuals, society, and global ethics.

8.1 Technology Maturation: Assessing the TRL (Technology Readiness Level)

The current state of "Smart" spine surgery reflects a bifurcated Technology Readiness Level (TRL). Local AR/VR-assisted navigation has reached **TRL 9 (Actual system proven in operational environment)**, with platforms like Augmedics' xVision receiving regulatory clearance and being used in thousands of successful clinical cases (Burström et al. (2021). [4]). However, 6G-enabled remote telesurgery is currently at **TRL 4–5 (Technology validated in lab/relevant environment)**. While 5G-based telerobotic spinal surgeries have been successfully performed in controlled pilot studies (Tian et al. (2020). [09]), the sub-millisecond latency required for high-speed active intervention via 6G remains in the experimental phase, pending the global rollout of 6G infrastructure and haptic-visual synchronization protocols (Ding et al. (2025). [6]).

8.2 Impact on Individuals: Patient Safety and Surgeon Longevity

The impact on the individual is primarily characterized by a significant enhancement in safety and physical sustainability. For the patient, the primary impact is the "Precision Dividend," where instrumentation accuracy rates nearing 98–100% minimize the risk of life-altering neurovascular complications (Chandan Reddy et al. (2025). [3]). For the surgeon, the technology addresses the critical issue of occupational longevity. By utilizing ergonomic robotic consoles and heads-up AR displays, surgeons can mitigate the chronic musculoskeletal strain and "surgeon burnout" associated with traditional, physically taxing spine procedures (Cofano et al. (2025). [5]). Furthermore, the 70–90% reduction in intraoperative radiation exposure provides a long-term health benefit for the surgical team, reducing lifetime cancer risks (Nadeem-Tariq et al. (2025). [2]).

8.3 Impact on Community & Society: Bridging the Urban-Rural Healthcare Divide

At the societal level, 6G-enabled telesurgery serves as a powerful tool for healthcare democratization. Historically, elite spinal care has been concentrated in urban "Centres of Excellence," leaving rural and underserved communities with limited access to specialized surgeons (Jha et al. (2026). [7]). The "borderless" nature of 6G connectivity allows for a "Hub-and-Spoke" model, where a single specialist at a central hub can perform or supervise procedures in multiple remote community hospitals simultaneously (Misra et al. (2025). [8]). This reduces the socio-economic burden on families who would otherwise face high travel costs and lost wages to seek specialized care in distant cities (Elendu et al. (2024). [61]).

8.4 Impact on Humanity: The Ethical Shift—Surgery as a "Borderless" Service

The ultimate impact on humanity is a fundamental shift in the ethical conceptualization of surgery. The decoupling of the surgeon's physical presence from the patient's bedside transforms surgery from a localized event into a globalized, "borderless" service (Ding et al. (2025). [6]). This prompts a significant ethical evolution regarding the "Universal Right to Precision," where geography should no longer dictate the quality of a life-saving intervention. However, this shift also introduces the "Responsibility Paradox," requiring humanity to develop new international legal and ethical frameworks to manage cross-border medical liability and the protection of sensitive digital anatomical data (Elendu et al., (2024). [61]). This transition signals the dawn of "Civilizational Health," where technology is leveraged to ensure equitable healing for all of humanity, regardless of political or physical boundaries (Aithal & Kumar (2015). [51]).

9. ETHICAL, LEGAL, AND MEDICO-LEGAL FRAMEWORK (ELSI) :

The transition to a "borderless" surgical environment necessitates a robust framework to address the complex ethical, legal, and social implications (ELSI) arising from the decoupling of the surgeon and the patient. This section explores the challenges of jurisdictional licensing and the privacy of virtual anatomical data.

9.1 Jurisdiction: Cross-border Licensing for Remote Surgeons:

One of the most significant legal barriers to 6G-enabled telesurgery is the determination of medical jurisdiction. Traditionally, a surgeon must be licensed in the specific state or country where the patient is physically located; however, remote surgery complicates this by allowing a surgeon in one jurisdiction to operate in another (Elendu et al. (2024). [61]). This creates a "legal vacuum" regarding which medical board holds authority in the event of malpractice or a network-related adverse event (Saceanu et al. (2015). [62]). To address this, current literature suggests the development of "Global Surgical Passports" or reciprocal licensing agreements that allow elite specialists to provide remote care across borders without the administrative burden of multiple national licenses (Jha et al. (2026). [7]). Without such frameworks, the clinical utility of telesurgery will remain restricted by political boundaries rather than technical capacity (Misra et al. (2026). [8]).

9.2 Data Privacy: Security of the "Digital Twin" of the Patient's Spine:

The "Smart" ecosystem relies on the creation of a "Digital Twin"—a high-fidelity, 3D virtual replica of the patient's spine generated from CT and MRI data. While this twin is essential for real-time AR navigation, it constitutes highly sensitive biometric information that is vulnerable to unauthorized access and "digital kidnapping" (Punitha et al. (2022). [63]). Protecting the security of this digital twin is paramount, as a breach could allow malicious actors to manipulate the surgical plan or gain access to a patient's unique anatomical identity (Ding et al. (2025). [7]). Current strategies for data privacy emphasize the use of "Blockchain-enabled Medical Data Management," where every modification to the digital twin is recorded on an immutable ledger, ensuring the integrity and confidentiality of the patient's virtual anatomy during transcontinental transmission via 6G (Li et al. (2026). [10]).

10. THE "LATENCY-HAPTIC" PERCEPTION GAP :

The "Latency-Haptic" perception gap represents a critical psychological and physiological frontier in 6G-enabled telesurgery. This section explores the "perceptual transparency" required for a surgeon to feel bone and ligament resistance from a distance of 1,000 miles.

In traditional "open" spine surgery, the surgeon relies on a high-fidelity haptic loop where the resistance of the cortical bone and the "give" of the ligamentum flavum are transmitted directly through the instruments to the fingertips. When these hands are placed at a remote master console 1,000 miles away, this physical loop is replaced by a digital "Haptic-Visual" synchronization (Ding et al. (2025). [6]), The primary exploratory challenge is the **"Perceptual Lag,"** where even a 50-millisecond delay in haptic feedback can lead to "sensory mismatch," causing the surgeon to over-pressurize a tool because they have not yet "felt" the bone's resistance (Misra et al. (2025). [8]). This desynchronization can result in a "penetration error" during pedicle screw placement, where the robotic arm may breach the vertebral wall before the remote surgeon receives the tactile warning signal (Jha et al. (2026). [7]).

Furthermore, the surgeon's perception is influenced by the **"Transparency Index"**—the degree to which the teleoperation system makes the master-slave link feel non-existent. Current 5G systems allow for "coarse haptics," but the "Smart" spine surgery paradigm requires 6G infrastructure to support **sub-millisecond tactile feedback (<1ms)** to achieve true immersion (Ding et al. (2025). [6]). Exploratory analysis suggests that when latency is reduced to this "imperceptible" level, the surgeon's brain undergoes "Proteus Effect" adaptation, where the robotic end-effectors are perceived as an extension of their own biological hands (Li (2026). [10]). However, the lack of "force-feedback granularity"—the ability to distinguish between different grades of bone density remotely—remains a significant constraint that necessitates the integration of AI-driven haptic amplification to "highlight" critical tactile markers for the remote operator (Tian et al. (2020). [9]).

Ultimately, the perception gap is not merely a technical latency issue but a cognitive one. Surgeons operating at a 1,000-mile distance report a "Tactile-Visual Conflict," where the 3D AR holographic overlay may show a screw entering bone while the haptic gloves remain momentarily "light" due to network jitter (Misra et al. (2026). [8]). To resolve this, futuristic 6G frameworks are exploring **"Predictive Haptics,"** where edge-computing algorithms predict the resistance based on preoperative CT density maps and "pre-transmit" the haptic sensation to the surgeon's gloves milliseconds before the robot makes physical contact (Ding et al. (2025). [6]). This ensures that the surgeon "perceives" the touch in perfect alignment with the visual feed, maintaining the "Psychological Presence" required for high-stakes neurovascular manoeuvres (Jha et al. (2026). [7]).

11. SUGGESTIONS & RECOMMENDATIONS :

Based on the multi-dimensional analysis of the 6G-enabled "Smart" spine surgery ecosystem, the following strategic suggestions are proposed to ensure the successful transition from experimental pilots to standardized clinical practice [199-200].

11.1 Strategic Recommendations for Policymakers (5G/6G Infrastructure):

To facilitate the "borderless" surgical service model, policymakers and healthcare administrators must prioritize the development of **Medical-Grade Connectivity Corridors**. Unlike general-purpose 5G/6G networks, surgical infrastructure requires dedicated "Network Slicing" to ensure that life-critical telesurgery data is prioritized over commercial traffic, maintaining a zero-latency guarantee (Ding et al., (2025). [6]).

(i) **Incentivizing Rural 6G Deployment:** Governments should provide tax incentives for telecommunication providers to deploy 6G nodes in rural and tier-3 hospital zones, specifically targeting regions with high urban-rural healthcare disparities (Jha et al. (2026). [7]).

(ii) **Establishment of a Global Medico-Legal Passport:** Policymakers must collaborate on an international scale to create standardized licensing for remote surgeons. This should include "Reciprocal Tele-Practice Acts" that define liability frameworks for cross-border interventions, ensuring that technical capacity is not throttled by legal friction (Elendu et al. (2024). [61]).

(iii) **Cyber-Physical Security Standards:** National health agencies should mandate the "Mirror Protocol" for all telesurgical systems, requiring end-to-end encryption and a physical "kill-switch" at both the master and slave nodes to prevent unauthorized network interference (Punitha et al. (2022). [63]).

11.2 Curriculum Suggestions for Medical Universities (Training "Digital Surgeons"):

The evolution from "Open" to "Smart" surgery necessitates a fundamental overhaul of surgical residency programs. Medical universities must move beyond traditional anatomy to cultivate a new generation of **"Digital Surgeons"** who are proficient in both biological and technological domains.

(i) **AR/VR-First Simulation Training:** Traditional "cadaveric labs" should be augmented with mandatory VR-based "Patient-Specific Rehearsals." Residents should be required to complete 100+ hours of high-fidelity VR simulations—focusing on managing latency spikes and "Tactile-Visual Conflict"—before being permitted to operate on a live patient-side robot (Kuhn et al. (2024). [1]).

(ii) **Interdisciplinary "Bionic" Curriculum:** Training should include modules on **Medical Robotics, Data Privacy, and AI Literacy**. Surgeons must understand the underlying algorithms of AR navigation to recognize when an AI-driven "Smart" trajectory may be suffering from data bias or sensor drift (Agrawal (2018). [65]).

(iii) **Cognitive Resilience & Remote Ethics:** Residents should be trained in the psychological aspects of "Remote Presence," learning how to maintain empathetic patient connections through a digital interface. This includes training in the "Mirror Protocol" for self-reflection and ethical resilience, ensuring that the distance of telesurgery does not lead to the dehumanization of the patient (Aithal & Kumar (2015). [51]).

12. CONCLUSION :

The exploratory analysis of 6G-enabled smart spine surgery reveals a profound technological shift from traditional visualization to an immersive, data-centric paradigm. The findings indicate that the integration of AR/VR technology and robotic assistance significantly enhances surgical precision, with instrumentation accuracy rates consistently reaching 98% to 100% in complex spinal procedures. Furthermore, the transition from 5G to 6G infrastructure addresses the critical "latency-haptic perception gap" by targeting sub-millisecond delays (<1ms), which is essential for the real-time transmission of tactile feedback over vast distances. This "Smart" ecosystem not only improves patient safety by minimizing neurovascular risks and reducing intraoperative radiation exposure by up to 90%, but it also promotes surgeon longevity through enhanced ergonomics and reduced mental workload.

From a stakeholder perspective, the ABCD analysis underscores that while high initial capital outlay and network bandwidth requirements remain significant constraints, the long-term benefits are transformative. The democratization of elite surgical expertise through "borderless" telesurgery offers a strategic imperative for bridging the urban-rural healthcare divide, allowing specialists to perform life-saving interventions in underserved regions via remote master-slave robotic architectures. However, the successful institutionalization of this technology requires a dual focus on developing medical-grade 6G connectivity corridors and overhauling surgical curricula to train a new generation of "Digital Surgeons" proficient in both biological and technological domains.

The final verdict on the future of smart spine surgery is that it is no longer a distant possibility but an emerging global reality. As 6G infrastructure matures toward TRL 9, the decoupling of the surgeon from the patient's bedside will transform spinal care into a borderless, latency-free digital service. This evolution signifies a fundamental shift toward "Civilizational Health," where technological innovation is leveraged to ensure equitable and precise healing for all of humanity. While ethical and medico-legal frameworks regarding cross-border jurisdiction and data privacy must be proactively established, the trajectory is clear: the future of spine surgery lies in an autonomous, interconnected digital ecosystem that prioritizes human safety and global accessibility over geographical constraints.

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